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Five years continuous recording of total and diffuse solar radiation at Kew Observatory

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Summary

The first complete five years' data, obtained at Kew Observatory during 1947-51, are discussed with reference to their main systematic and random errors, the methods of correcting them, and the calibration techniques employed.

Corrected hourly means for 10-day periods are presented, after removal of all known errors, for T, D (total and diffuse radiation on a horizontal surface), S (duration of bright sunshine) and I (direct radiation normal to the beam).

The self-consistency of the data is examined, and useful inter-relationships are outlined. Diurnal variation is given for each of the four seasons, and the luminous efficiency of radiation discussed. Practical details are interposed whenever they are thought to be useful to other workers.

1. Introduction

Total and diffuse solarimeters were installed at Kew Observatory in 1946 to record the radiation received on a horizontal surface from sun and sky, and from the sky alone. Continuous recording of these components commenced in July of that year and has been maintained ever since. The data discussed in this paper are for the first complete five years of recording, namely 1947-51, but some reference will be made to selected occasions from 1952-53, when diurnal curves are constructed for cloudless and overcast days (see Sec. 8). No significant changes have been made in the installation during the period.

Provisional results based on the first fourteen months of recording (July 1946 to August 1947) have already been quoted by Stagg (1). The basic tabulations from which these were derived contained certain computational errors, and small systematic errors due to use of provisional instrumental factors which have since been revised. In addition, the allowances for incomplete exposure of the instruments were incorrect. The theory, calculations and experimental evidence for the present treatment of these obstruction corrections are given in Secs. 4 and 7. Sufficient practical details are included for corresponding corrections to be computed and applied at other observing stations.

In order that any previously published data may be related to the results found below, a conversion table is given under Table I. Since the corrections to total radiation involve a knowledge of the corresponding diffuse radiation at the time, the relations between total and diffuse radiation under various conditions, given in Sec. 8, can be used to obtain sufficiently accurate data by direct means.

The instruments used are two Moll-Gorczynski solarimeters obtained from Messrs. Kipp and Zonen. These thermopiles, having 14 thermojunctions and covered by two hemispherical glass domes, have been thoroughly discussed by Bener (2). Their purpose is to measure the short wave radiation from sun and sky. Since the glass domes transmit nearly all radiant energy in the waveband 0.3 μ to 3.0 μ , this purpose is achieved for all practical purposes. In this connection, see also Sec. 3.

2. Disposition of instruments and recording equipment

The instruments are mounted horizontally on the south balustrade of the Observatory. Behind them (to the north), the Observatory dome rises 14 feet above the instrumental horizon at a distance of 18 feet. Each solarimeter is surrounded by a circular guard-plate in the same plane as the sensitive surface of thermojunctions. This has two functions, firstly to prevent radiation from below the horizon reaching the thermopile after refraction at the domes, secondly to moderate the temperature variations of the case (and hence, also, the cold junctions) by shielding it from the direct rays of the sun.

For the diffuse recording thermopile, a circular metal band is mounted on a polar axis so that, with slight movements up or down the axis to allow for changing declination, the sun's direct radiation is prevented from falling on the solarimeter. From the beginning of recording until June 1951, the width of the band was 18 mm, the radius being 135 mm. After this date the band's width was increased to 29 mm to prevent loss of record due to incomplete shading, (the band is only moved along its axis on days when the sun is shining clearly enough to cast a shadow across the thermopile). * Condensation inside the domes is prevented by connecting the air-space to a tube of silica-gel.

The output from the two solarimeters is taken first to the Observatory dome, and then inside the building to a Cambridge thread-recorder in the basement. This contains three circuits which are connected in turn at minute intervals. One records the output of the total solarimeter, the second that of the diffuse solarimeter, and the third marks the baseline. The latter circuit is interrupted at the hour to give a time-mark. From the calibration factors of each instrument (see Sec. 3) suitable series resistors are included in the thermopile circuits so that under overcast skies the two traces will fall together. Apart from being a continual check on the continuity of the circuits, this method of display facilitates subsequent analysis of the data, particularly when selecting overcast periods (see Sec. 8).

3. Calibration of the records

The standard of radiation at Kew is based on readings of the Ångstrom compensation pyrheliometer, which has unshielded black strips. Radiation intensities derived from the Moll solarimeters are in effect the intensities incident on the unprotected thermopile surfaces, provided the solar radiation transmitted by the two glass domes bears a constant relation to the total radiation falling on the outer surface of the glass. Apart from the constant fraction of some 15% lost by non-selective reflection at the four glass surfaces (the additional dome was added to reduce variations of sensitivity with sun's altitude, attributed to formation of caustic curves)/ , there is only a minute fraction of the radiation lost by absorption. Consequently when factors are chosen, relating the thermopile readings to those of the Ångstrom pyrheliometer, they yield close approximations to the actual radiation intensities, under all conditions.

Two Ångstrom pyrheliometers, Nos. 24 and 100B, are used to standardise the other instruments. Based on the "uncorrected Ångstrom scale" and calibrated at Uppsala, these have recently been shown to agree within 0.3%. Investigations at the National Physical Laboratory (3) and at Kew (4) have shown that there has been no appreciable change in recent years in what may be termed the "Kew scale". The tabulated data dealt with in this paper are therefore based on the uncorrected Ångstrom scale, in which the solar constant according to Nicolet (5) is equal to 1.96 cal/cm^2/min. In accordance with current international policy, the basic data, which were tabulated in cal/cm^2/hr, are converted here into mw/cm^2. (1 cal/hr = 1.162 mw).

/During

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* Footnote: a white card, with a circular hole for the glass dome, greatly facilitates the adjustment in weak winter sunshine.

/ Footnote: it also has the practical advantage of stabilising zero drift during periods of fluctuating intensity.

During the period concerned, minor variants of calibration procedure have been adopted by successive members of the staff. These may be briefly outlined together with the method adopted at present. The most direct, though not always the most convenient, is to take a series of Angström readings on a bright cloudless day, meanwhile alternately shading and unshading the solarimeters from the direct rays of the sun. Difficulties and sources of error are numerous. Even on apparently cloudless days (or nearly cloudless, if the existing cloud is well away from the sun), there may be rapid fluctuations of direct solar intensity, due to patches of haze or invisible high cirrus. This often means that the sample of intensity measurements (by the pyrheliometer) may not always be a representative indication of the average intensity during the period of calibration. Then also, the accuracy of the method is dependent on the sky conditions being the same for both shaded and unshaded periods, since we are, in fact, equating:-

$$I \sin h \equiv T - D$$

where I is the direct intensity, h the sun's altitude, and T, D the unshaded and shaded readings respectively.

The practice at Kew has been to calibrate the records as a whole, i.e. solarimeter, leads, resistors and thread-recorder galvanometer combined. This has one disadvantage in that only one dot is marked on each trace during a three-minute period, and this sets the minimum time for shading at $3\frac{1}{2}$ mins. so as not to miss a dot. The shade used is a circular disc, of 2 inch diameter, silvered against the sun and dull black facing the instrument. It is mounted as far away as is convenient, usually some two or three feet distant from the thermopile centre. In the case of the diffuse thermopile, the shade ring is first lowered below the instrumental horizon.

Among other radiation equipment at Kew is a Moll-Gorczynski pyrheliograph which records on a second galvanometer, adjacent to the one which registers the total and diffuse components. The two galvanometers are encased within a single thread-recorder and, as a result, the dots on the two charts are made simultaneously. This allows the pyrheliograph to be used as the standard of direct beam intensity (calibration of this against the Ångström instrument being a straightforward procedure) and hence the standardisation only requires the shading and unshading of the two solarimeters by one observer. Timing errors are completely removed by this technique.

Finally, as an additional check, another solarimeter, which is maintained as a secondary standard, is repeatedly compared with the Ångström pyrheliometer throughout the year (its output being measured instantaneously by potentiometer). The output of this is now compared periodically with that of each of the continuous recording solarimeters, this being possible on a large number of days since the component for comparison is total (sun and sky) radiation, and periodic shading is thus not required.

4. Exposure of the instruments

(a) Errors of obstruction

The instruments are exposed on the south roof of the Observatory, at a point where some 8% of the north sky is obstructed by the Observatory dome, and a further 1% by trees along the remaining arc of the horizon. In addition, the shade-ring of the diffuse recorder obstructs a variable fraction of the sky, according to the setting of the ring, which depends on the sun's declination.

In assessing the correction for obstruction of the horizon it must be emphasised that the term to be computed is the fraction of the vertical component of the incoming flux, which is lost by obstruction, and not the fractional solid angle of the sky obscured *. To obtain an analytical expression for this fraction, we must assume an idealised model of an isotropically diffusing hemisphere, over the surface of which a quantity I of radiative energy is emitted normally from unit area in unit time.

/Fig. 1

* Footnote: the incorrect method was used at Kew during the period under investigation, and is embodied in M.O. Instrument Instruction No.225, which is being amended.

Fig. 1 shows an elementary area at P(r, θ, ϕ), part of an annular ring ABP at an elevation of θ above the horizon. The radiative energy emitted by this element in the direction PO will be $\propto I.r\cos\theta\, d\phi.r\, d\theta$. If we further assume that the receiving surface of the solarimeter is perfect (i.e. it conforms to Lambert's cosine law), then response of horizontal surface at O is:-

$$\propto Ir^2 \sin\theta \cos\theta\, d\theta\, d\phi$$

Similarly, response to whole hemispherical radiation is:-

$$\propto Ir^2 \int_0^{2\pi} d\phi \int_0^{\pi/2} \sin\theta \cos\theta\, d\theta$$

$$\propto Ir^2.2\pi.1/2 = \pi.\, Ir^2$$

The fraction of the vertical component, lost by obstruction of the elementary area at P, is therefore given by:-

$$\pi^{-1}\sin\theta \cos\theta\, d\theta\, d\phi.$$

In practice, we are concerned with correcting the diffuse radiation for obstruction by the shade-ring, and both diffuse and total radiation for obstruction by the Observatory dome and surrounding trees. The principle of the method in use is identical for both corrections. For obscuring objects of finite size, we write the expression:-

$$\pi^{-1}\iint \sin\theta \cos\theta\, d\theta\, d\phi \qquad \text{as} \quad \pi^{-1}\sum(\overline{1/2 \sin 2\theta}.\, \Delta\theta.\, \Delta\phi).$$

The outline of any given object is mapped out on a $\theta - \phi$ diagram, θ the elevation being ordinate, and ϕ the azimuth being abscissa. In the case of buildings or trees, this is conveniently done with a theodolite. Their projections onto the $\theta - \phi$ diagram are divided into suitable component areas over which a mean value of $\frac{1}{2}\sin 2\theta$ can be assigned (allowing for the non-linear variation of this quantity). The units of area, in terms of small squares counted on graph paper, or planimeter units, are translated into $(\text{radians})^2$. For instance, the area 5° in azimuth x 5° in elevation $\equiv$ 25 $(\text{deg.})^2 \equiv$ 0.00763 $(\text{radians})^2$.

The shade-ring correction which is variable according to the sun's declination, has been checked in two ways at Kew, either of which may be used. Since the ring is adjusted almost daily, so as always to interrupt the direct beam of the sun, it is possible to formulate an analytical expression for the projection of the ring on the $\theta - \phi$ diagram, when the sun's position is known. Fig. 2 shows how the shade-ring is mounted on a polar axis, by inclining the fixture towards the north, at an angle λ to the horizontal, where λ is the latitude of the station. When the ring AB is set so as to shade the solarimeter M at a given time, then, as the earth rotates, successive arcs of the ring will continue to obstruct the direct solar radiation, since the declination δ of the sun may be considered constant over short periods. The declination is here seen to be the angle between the direct beam and the equatorial plane.

Turning to the system of orthogonal axes in Fig. 3, we have the axis of the ring in the zy plane, at an angle λ to the y-axis. The plane of the ring is distance 'a' from the solarimeter (at the origin). The equation to this plane is therefore given by:-

$$x \cos \pi/2 + y \cos\lambda + z \sin\lambda = a.$$

To transpose into spherical polar co-ordinates, we use

$$\left.\begin{aligned} x &= r\cos\theta \cos\phi \\ y &= r\cos\theta \sin\phi \\ z &= r\sin\theta \end{aligned}\right\} \quad \phi \text{ measured +ve from east through north}$$

/whence

whence $r \cos\theta \sin\phi \cos\lambda + r \sin\theta \sin\lambda = a$

and $\cos\theta \sin\phi \cos\lambda + \sin\theta \sin\lambda = a/r = \sin\delta$.

Finally since:

$$\sin\phi = \frac{\sin\delta - \sin\theta \sin\lambda}{\cos\theta \cos\lambda}$$

and δ, λ are both known, we can express ϕ in terms of a single variable θ.

The alternative method, referred to, was used as a check, because isopleths of the sun's position at Kew had already been drawn on a $\theta - \phi$ diagram, together with the time of day. This was done by using the relation:

$$\sin A = \frac{\cos\delta \sin t}{\cos\theta}$$

where A is azimuth (measured +ve from south through west) and t is the sun's hour angle. Values of θ, for given t, were also available from isopleths based on:

$$\sin\theta = \sin\lambda \sin\delta + \cos\lambda \cos\delta \cos t.$$

The $\theta - \phi$ curves for the sun's position are identical to the projection of the shade-ring on the same diagram, and can be used as guide lines to complete the projections of the two rims of the ring.

The last stage requires the analytical representation of the projection of the two rims. Returning to the equation to the plane of the ring, for which we obtained:

$$r \cos\theta \sin\phi \cos\lambda + r \sin\theta \sin\lambda = a = R \tan\delta$$

where R is the radius of the ring, and $\tan\delta = a/R$, we add the remaining conditions given by:

$$a_1 = R \tan\delta - d \qquad a_2 = R \tan\delta + d$$

where d is the half-width of the ring, (see Fig. 4).

Also: $r_1^2 = a_1^2 + R^2 = R^2 + (R \tan\delta - d)^2$

and $r_2^2 = a_2^2 + R^2 = R^2 + (R \tan\delta + d)^2$.

Thus: $r_1 \cos\theta \sin\phi \cos\lambda + r_1 \sin\theta \sin\lambda = R \tan\delta - d$

and $r_2 \cos\theta \sin\phi \cos\lambda + r_2 \sin\theta \sin\lambda = R \tan\delta + d$.

The general equation for both rims is therefore given by:-

$$\cos\theta \sin\phi \cos\lambda + \sin\theta \sin\lambda = \frac{R \tan\delta \pm d}{\sqrt{(R \tan\delta \pm d)^2 + R^2}}$$

Substitution in this equation at a series of points will complete the projection of the shade-ring for any required date. Alternatively, pairs of points can be determined near sunrise ($\theta \sim 0°$) and near midday ($\phi \sim 270°$), and "french curves" used to complete the profiles, with the curves of sun's position as guide lines. The areas obtained are split into convenient parts (say between $\theta = 0°$ and $\theta = 10°$, etc.) over which values of $\sqrt{\frac{1}{2} \sin 2\theta}$ may be conveniently assigned, and the final correction: $\pi^{-1} \Sigma(\sqrt{1/2 \sin 2\theta}. \Delta\theta. \Delta\phi)$ is then computed.

/(b)

(b) Effect of back reflection

The following considerations apply to the particular exposure of the Kew installation. At most other sites, it would be permissible to regard the shade-ring and permanent obstructions as cutting off the fractions of diffuse radiation as determined by the method given above. At Kew, however, lack of space has necessitated the solarimeters being placed comparatively close to the Observatory dome, which consequently subtends a large solid angle, especially in the vertical. ⁂

With such an arrangement, it was necessary to make measurements of the back-reflection from the dome under various conditions of sun and sky. For this purpose, a Linke-Feussner radiometer with glass filter was directed at various parts of the roof, and at the surrounding sky. The dome proper is a dull black; the cylindrical part being a somewhat weathered cream (see Fig. 5). This accounts qualitatively for the values shown in Fig. 6, which were obtained on a bright sunny day. The vertical axis of reference in Fig. 6 is the direction of the centre of the dome viewed from the radiometer, which was placed close to the solarimeter. From the two traverses made, (one in the horizontal, one in the vertical), mean values have been deduced for the separate parts of the dome; these are shown thus: [10.0]. Finally, integrating the contributions to obtain the fraction of the diffuse radiation gained by back reflection, we have:-

$$\frac{\sum I_n . \overline{1/2 \sin 2\theta} . \Delta\theta . \Delta\phi}{\pi I}$$

where I_n is the radiation intensity from each part of the dome emitted in the direction of the solarimeter. Also, since πI is the integrated effect of the whole hemisphere on the receiver, we can insert the measured value given by the diffuse recorder at the time the measurements were made.

Inserting the intensities found, we obtain for the percentage contribution due to the dome, the figure of 4.5%. The diffuse radiation obscured by the dome amounts to some 2.5%. Having fixed the upper limit in this way, it is now possible to estimate the mean contribution for all conditions, or the particular figure applicable to any selected occasion. ⁄

5. Instrumental errors: temperature coefficient and cosine law

There is little disagreement on the accepted value of the temperature coefficient of the solarimeters used and experiments made at Kew agree closely with the coefficient given by Bener (2) namely 0.25% per 1°C over the normal range of ambient temperatures, the sign being negative. On the question of cosine law deviations there is less accord and this is probably due partly to real differences among instruments of the same type, and partly to variations in investigational technique.

To obtain valid data on this question, the solarimeter should be in the horizontal position, since the pattern of convection within the glass domes is sufficiently affected to alter the output of the thermopile if the instrument is tilted. In this country, natural opportunities to test the

/cosine

⁂ Footnote: see Sec. 12 regarding the improved installation which has been completed recently.

⁄ Footnote: the application of this correction to the basic data is discussed in Sec. 7.

cosine law (when the sun is at various altitudes) are few and far between. The use of an artificial laboratory source is therefore advantageous. A 2000 W tungsten-filament projector lamp, slightly under-run for stability, is used to irradiate the solarimeter under test at various elevations above the instrumental horizon. A rigid link between the lamp support and the solarimeter ensures the constancy of their separation. Fig. 7 shows a typical response curve found at Kew, and also some data due to Bener (2) 9.

Added to the simple variation of sensitivity with elevation is the azimuthal effect, which appears to be similar for most instruments. The following data refer to two standard thermopiles, orientated so that the longer line of thermo-junctions faces the directions given, with the artificial sun assumed always to the south:

	Longer line of junctions facing:	E	S	W	N
Response (arbitrary units)	1st pile:	87	63	83	74
	2nd pile:	85	61	81	70

The elevation during this test was kept constant at 15°; at higher angles the effect diminishes rapidly. In normal recording, the amplitude of the variation is markedly reduced by the presence of the diffuse component in the case of the total solarimeter; there is a negligible effect on the diffuse instrument.

No corrections have been made to the Kew data for errors due to the azimuthal effect, but the magnitude of the variation is sufficient to warrant the recommendation that, in future installations (see Sec. 12), all thermopiles be orientated in the same direction.

Returning to consideration of the combined effect of imperfect cosine law response and temperature coefficient, it is calculated that the diffuse solarimeter will read low by ~ 0.5% on the first account and will not be greatly affected by the second factor from hour to hour. Corrections have not, therefore, been applied here, though there exists a long term annual variation of ~ 3%. In the case of the total solarimeter, typical magnitudes of these errors may be usefully compared. Calibrations are most often done at high solar altitudes and consequently high ambient temperatures, and it is found that there is little significant trend in the calibration factors during the year. Thus, the assessment of possible errors is to be related to departures of natural conditions from those of the ideal calibration periods. In winter, with the sun at an altitude of 15°, a cosine law error of -2.6% (Fig. 7, Bener's curve) is to be compared with the effect of a fall in ambient temperature of some 10°C below summer values, giving a compensating increase of +2.5% in the thermopile output. Again, the best approximation is to assume the mutual compensation of the two errors.

6. Tabulating errors: random and systematic

The basic tabulations, on which subsequent sections are based, are obtained by estimating the mean intensity for the hours in question by placing a graduated transparent scale over the thread-recorder charts. Considerable random errors may be introduced by this procedure, especially on days of rapidly fluctuating intensity caused by broken clouds or haze patches. A series of trials has been carried out in which many charts were measured independently by different observers. Fig. 8 shows the ogive derived from independent tabulations of charts of total daylight illumination (which are closely similar in appearance to those of total radiation). Denoting the two estimations of each hourly tabulation by L and L', then one month's data (August 1950) were analysed in the form: $\left(\frac{L - L'}{L} \times 100\right)\%$, in 5% ranges. Errors expressed in this way can amount to 50% due to rounding off to the nearest whole number at very low intensities.

/Fig. 9

9 Footnote: Bener's data refer to the instrumental response to total (sun + sky) radiation, the Kew curve only to a direct beam.

Fig. 9 shows the ogive derived from independent tabulations of total radiation indicated on different recorders by two similar solarimeters. The estimations are here denoted by T and T_1 and expressed in the same way as before, three months' data (April and May 1949, June 1950) being taken together. Considering the implications of both these ogives, we can (insofar as the errors approximate to a normal distribution) obtain a reasonable estimate of the standard deviation (6). If the abscissae corresponding to ordinates of 16% and 84% are noted, then the range between them is equal to 2σ . From Fig. 8, σ = 7% and there is a systematic error of $2\frac{1}{2}$%; from Fig. 9, $\sigma = 5\frac{1}{2}$% and the systematic error is 4%. Apart from the slightly larger systematic error in the second case (which could easily arise from a small discrepancy in one of the calibration factors in use at this period), there is no significant difference in the two trials. This implies that the tabulating errors outweigh errors due to small differences in similar instruments. Finally it should be noted that the standard deviations obtained refer to the combination of two independent sets of estimates. The probable magnitude of errors of tabulation is therefore $1/\sqrt{2}.\sigma$ or about 5%.

The problem of eliminating errors of chart measurement has recently been attacked by automatically integrating a solarimeter's output, to give daily totals (7). It is hoped to extend this method to hourly totals.

7. The corrected hourly means

To summarise briefly the treatment of the data necessary to remove all known systematic errors, we have first the obstruction corrections. Though the Observatory dome obscures 8% of the hemisphere, the resultant loss of radiant flux is computed to be only $2\frac{1}{2}$% (assuming a perfectly black dome). When back reflection is included, we have the practically determined contribution of $4\frac{1}{2}$%, (on a cloudless day). The average cloud amount at Kew is about 5/8 and hence, to the degree of accuracy required, we consider average days to have a uniform distribution of 5/8 cloud. For 5/8 of the time, the sun being obscured, the dark dome is seen against the relatively bright sky ⁂. Under these conditions the dome is about half as bright as the surrounding sky, giving say $1\frac{1}{4}$% of the diffuse radiation. For 3/8 of the time the sun shining on the dome makes it about $1\frac{1}{2}$ times as bright as the surrounding sky (the same as before), and the contribution becomes about $3\frac{3}{4}$% of the diffuse radiation. If the dome were replaced by the sky it obscures, the contribution would be simply $2\frac{1}{2}$%. Hence, to a close approximation, the dome has no appreciable effect on average values. The only allowance made here is for cloudless days (see Sec. 8) where the greatest effect is found, namely a gain of 2% over the diffuse radiation at a perfectly exposed site.

In addition to the permanent obstructions, which affect the exposure of both instruments, the shade-ring correction must be applied to the diffuse radiation tabulations. As previously described in Sec. 4, the percentage loss of diffuse radiation (assuming isotropic scattering) is determined by the dimensions of the ring and the declination of the sun.⁄ The original tabulations included 3% for the shade-ring and 9% for permanent obstruction in mid-winter, involving an addition of about 14% to the measured diffuse radiation. When the correct method of computing the shade-ring allowance is used, and the average permanent obstruction contribution is assumed to be zero, the revised correction is reduced to 1%. The mid-summer figures of 7% and 9%, or 19% to the measured value, are reduced to 8%. The mean difference between the two corrections is therefore 12% for most of the period concerned, and 14% after the change to a broader ring in June 1951.

/Two

⁂ Footnote: it is shown in Sec. 8 that the diffuse radiation is higher for average days (5/8 cloud) than for cloudless days.

⁄ Footnote: unlike the dome's surface, the shade-ring is dull black and produces negligible back-reflection.

Two further errors, allowed for in the corrections to previously published data given under Table I, were: the omission of the permanent obstruction correction to the diffuse radiation, during June 1947 to December 1949, although included in the total radiation tabulations; and secondly, the makers' provisional calibration factors, used during the period, were altered slightly after sufficient experimental evidence had been acquired. Table I is extended up to the present time for completeness, and because some 1952-53 data are used in the next section.

The basic tabulations, which have necessarily been corrected retrospectively, are presented in Table II (total) and Table III (diffuse) in the form of hourly means for 10-day periods. Thus June 0, 1, 2 refer to the first, second and last 10-day period in the month (i.e.: 1st to 10th, 11th to 20th, 21st to end of month). It was shown in Sec. 6 that the standard deviation of a single tabulation is of the order of 5%. The random errors in the 10-day means, representing five years' data, are therefore reduced to about 1% since each is based on 50 observations.

8. Diurnal variation of total and diffuse radiation

Stagg (1) has described the sky conditions which produce the extreme values of total radiation (T) and diffuse radiation (D), together with the variations (with cloud type and amount) of these components. To supplement these figures, data have been extracted to construct diurnal curves for cloudless and overcast days. A preliminary selection of the 1947-51 material gave an insufficient number of suitable occasions and therefore, for this section only, data for 1952-53 have been incorporated. For comparison, the average day curves derived from Tables II and III have been included.

Figs. 10 and 11 show curves of diurnal variation (all days included) for the months of March, June, September and December, in which the components are T and D respectively. There is a high degree of symmetry about noon L.A.T., with a slight tendency for the forenoon values to be a little higher than those of afternoon. How much of this may be due to temperature coefficient, and how much to the diurnal change in cloud form (small cumuliform cloud in the morning would tend to give higher intensities than the denser cumulus or cumulonimbus of afternoon), it is not possible to decide. Certainly there is little evidence for any markedly asymmetric variation. In this connection, however, it is of interest to note that whereas the diffuse radiation tends to be high in the forenoon, the direct component I sin h is correspondingly low. The result is the comparative smoothness and symmetry in the T curves.

Figs. 12 and 13 show curves of diurnal variation on cloudless days, for D and T respectively, for the same four months. These are meant to represent the average cloudless day, which may be affected to a greater or lesser degree by the smoke pollution encountered in the Greater London area. It is thought that these curves will be representative, therefore, of the actual climatic conditions in which most people live in this country.

The method of selecting the data for these curves consists of examining the original charts for the hours during which the T and D traces were smooth and well-separated. At the same time, the sunshine tabulations were required to indicate 100% sunshine, and the Gorczynski pyrheliograph to give a smooth unbroken trace. Finally, the recorded observations were required to show 1/8 cloud or less for at least three consecutive hours. In cases of doubt, the end hours of these periods were rejected. The remaining tabulations were re-tabulated under time of day and the means corrected for systematic errors. This procedure was identical to the removal of errors from the hourly means for 10-day periods, with the single exception that the D values were reduced by 2% for back-reflection from the dome.

/In

In Fig. 13 the curves for T are again smooth and regular with a suspicion of higher morning values. The D curves in Fig. 12 are given more tentatively because of the much greater variability experienced, according to the haziness of the atmosphere. Even more data are required before mean curves can be drawn objectively. There does seem, however, an indication that the March and September curves are asymmetric; the former being higher in the afternoon, the latter in the morning. Since cloud has been eliminated as a variable, we may look to the complex effects of the atmosphere's content of water and smoke pollution.

The former will have different significance in the liquid drop phase (say in early morning) and in the vapour phase (afternoon). The latter will make a variable contribution (for the same total amount) according to whether it is concentrated in a shallow layer beneath an inversion (morning) or distributed in depth by convection (afternoon). These complex factors can not be quantitatively assessed as yet.

Fig. 14, similarly, is given as a general guide to the orders of magnitude of the intensities to be expected on overcast days. The curves are less definite around midday, due to the smaller number of observations. By definition, T and D must be equal, and therefore only tabulations of T have been used to construct the curves. The method of selecting the data consists of choosing periods when the T and D traces were approximately coincident, when the sunshine tabulations indicate no sunshine, and when the Gorczynski pyrheliograph gave no deflection. Finally, the observations were required to show 7/8 cloud or more for at least three consecutive hours. In cases of doubt, the end hours of these periods were again rejected. The remaining tabulations were similarly corrected after obtaining the means for each hour, for the same four months. The values found are similar but slightly less than the corresponding curves for cloudless days (D).

9. Comparison with direct radiation

It was mentioned in Sec. 3 that the basis of calibration of the T and D solarimeters lies in the equation:

$$I \sin h \equiv T - D.$$

It is therefore of interest to examine how closely this criterion of accuracy and self-consistency is adhered to in the course of continuous recording. For this purpose, hourly means of I for 10-day periods are presented in Table IV for the same years (1947-51) as for T and D.

During this time, I was recorded by the Moll-Gorczynski pyrheliograph, which received a complete overhaul in 1945 as described in G.M. 86. Its sensitivity remained unchanged until October 1949 when the Richard recording millivoltmeter was moved from the Observatory dome down to the basement. This appears to have increased the sensitivity of the recorder by about 5%; at the same time the blacking on the thermopile gave signs of slow deterioration (about 1% by the end of 1950). The data for October 1949 to December 1950 have therefore been multiplied by the factor 0.96.

Due partly to the uncertainty of the Richard millivoltmeter sensitivity, and partly to unsatisfactory performance of the pyrheliometer heliostat at this time, data for 1951 have been obtained from the records of the twin-mounted thermopiles (referred to in G.M. 86) which were formerly used for measuring spectral components of the direct radiation. These instruments and their thread-recorders have remained unchanged since they were first used in 1947. Before the end of 1949, the filters were removed and the outputs of the two thermopiles superposed on a single chart.

Denoting the originally tabulated readings of the single pyrheliograph by I_1, and those of the twin-mounted thermopiles by I_2, it was found that I_2 was correct in 1950, when referred to the standard Ångstrom pyrheliometer. Comparisons of I_2 and I_1, on numerous occasions during this year, show that I_1

/was

was the greater by about 4%. Since the multiplying factor of 0.96 (used above to correct the I_1 data) brings the two sets of data into full agreement, there is satisfactory confirmation, both for the use of the 1950 corrected I_1 data, and for the inclusion of the 1951 I_2 data in the five year means without introducing inhomogeneity into the material. Actual standardisations during 1951 show that I_2 was still in agreement with the standard.

The most serious source of error in measurements of direct radiation arises from incorrect adjustment of the heliostat mechanism. Thus systematically low values of order 10% can frequently occur in spite of accurate standardisations, which are only done after the alignment of the instruments has been checked. Ogives were drawn, as in Sec. 7, for independent tabulations of the same direct radiation charts. For these, σ = 12% with no systematic difference. Thus the tabulation errors ($1/\sqrt{2} \cdot \sigma = 8\frac{1}{2}\%$) are slightly larger than the corresponding errors in T and D, due to the more intermittent character of the records. Further ogives were drawn for sets of routine tabulations of I_1 and I_2 recorded on different instruments. Here, σ = 18% with a systematic term of 5% (I_1 being the lower). Since the I_2 heliostat is electrically driven and the I_1 clock-driven, the increased scatter ($1/\sqrt{2} \cdot \sigma = 13\%$) is to be expected, and it is known that the clock drive was less satisfactory at the time, giving more trouble on the I_1 record.

Since there are no cosine law errors, the only remaining systematic errors are due to temperature coefficient which gives an annual variation of about 3% between summer and winter. No correction has been made for this. In Fig. 15, the hourly means for (T - D) are plotted against I sin h; the continuous line represents the state of complete self-consistency. Apart from the further emphasis on the magnitude of the routine tabulating errors, it is clear that residual systematic errors will require further attention in the future. The low values of I sin h reflect the problem of accurate alignment on the sun, and the departure from the isotropic scattering of diffuse radiation (assumed in Sec. 4) will result in the shade-ring obscuring more than the computed fraction of D, thus giving high values of (T - D).

10. Total radiation and daylight

The measurements, so far considered, concern the range of wavelengths 0.3μ to 3.0μ ; it is of interest to compare them with the illumination measurements previously reported (8). In most countries, radiation data are more numerous than daylight illumination figures. The latter could often be deduced from the former, therefore, if a sufficiently close correlation was shown to exist between them. The continuous recording of daylight at Kew offers a favourable opportunity for examining the ratio of daylight intensity: radiation intensity (in units of lumens per watt), which is known as the luminous efficiency of daylight.

Tentative values of this ratio were given in (8); these were derived from the diurnal curves of T and L (daylight) for cloudless occasions. More recent work enables a clearer picture to be drawn, and the analysis can be extended to all occasions.

In the course of an investigation on the albedo of the atmosphere (9), the cloudless and overcast periods (such as those used in Sec. 8) were analysed under ranges of solar elevation. The L.E. (luminous efficiency) for cloudless periods was found to be remarkably constant for all solar angles (125 ± 2), but increased slightly for overcast periods with higher elevations. This may have been a feature of the sample taken, however, the mean L.E. being similar to the previous value (126 ± 5). This suggests that useful results might be obtained by assuming the approximate constancy of L.E. with sky conditions, for a given time of year. When all occasions are considered together (omitting only the hours in which sin h $<$ 0.1), the L.E. is little changed (123 ± 3). The mean deviations here refer to the scatter of the means for each sin h range: 0.1 - 0.2, 0.2 - 0.3, etc.

/Any

Any slight trends in the mean luminous efficiencies reflect the increase of winter observations in the low sin h ranges and vice versa. To test the annual variation of L.E., the midday hours (11 - 12, 12 - 13, for all occasions) were extracted for each 10-day period from Table II of this paper and Table II of reference (8). These were averaged to give the monthly means of L.E. set out below:

J	F	M	A	M	J	J	A	S	O	N	D
113	113	110	119	122	128	133	132	134	122	123	112

Again, the mean value is nearly the same as before (122 ± 7). Approximate values of daylight illumination (on a horizontal surface) can therefore be deduced by using these monthly means of L.E. irrespective of cloud amount or time of day. It must be emphasised, however, that these somewhat tentative results are only relevant to the five year period considered, to the respective instrumental methods of measurement and to the local conditions of exposure and climate.

11. Total radiation and sunshine

In the previous section, conversion factors were given by means of which daylight illumination data could be derived from available radiation data. Of much greater need and wider application is a method of using the abundant measurements of the Campbell-Stokes sunshine-duration recorders to estimate daily values of total radiation.

A well-known formula, due to Ångström, has the form: $Q = Q_o(a + bS)$ where a and b are constants such that $a + b = 1$, S is the %age possible sunshine, and Q_o is the radiation under clear skies. The equation gives approximate values of Q, the total radiation actually received, for typical average days when the cloud cover is near the normal (e.g. about 5/8 at Kew).

It is proposed to depart from this method for three reasons. In the first place, although a linear relation can be found* to fit the data for cloud amounts between half and total cover, it grossly overestimates the radiation on cloudless days. Secondly, if a is found by putting: S = 0 (overcast days), and b adjusted accordingly, then the radiation deduced for any cloud amounts near the normal value will be underestimated. This results from the fact that cloud layers which conform to the conditions selected for overcast periods are much denser than at other times, giving a low figure for the constant a. Lastly, a much more relevant and practical point is that if cloudless day values are known, there is every likelihood that there is no need to deduce radiation data from sunshine data.

The problem has therefore been approached from the standpoint of an investigator possessing only records of the Campbell-Stokes instrument, and a knowledge of the extraterrestrial radiation falling on a horizontal surface. Table V gives hourly means of extraterrestrial radiation for 10-day periods based on Nicolet's data on the solar constant (5). These were summed cross-ways to give the corresponding daily totals (which will be denoted as Q_{Ext}, and apply to any station in the same latitude as Kew: 51° 28' N).

The hourly means of sunshine duration for 10-day periods are presented in Table VI, again for the same years (1947-51). After summing these cross-ways, the daily totals were compared with the length of day (obtained from times of sunrise and sunset at Greenwich) to give the %age possible sunshine, S. For each of the year's 36 decadal periods, values of Q/Q_{Ext} were plotted against S. As shown in Fig. 16, all these points lie between values of S from 15% to 55%. To complete the diagram, the curves in Figs. 13 and 14 were integrated to give the overcast Q/Q_{Ext} for S = 0, and the cloudless Q/Q_{Ext} for S = 100. The probable trends of the ratios Q/Q_{Ext} have been sketched in for the four months March, June, September and December.

/The

* Footnote: but only if the condition that a + b = 1 is relaxed.

The final result makes it clear why no simple linear regression equation can be found to fit the observed radiation over the whole range of cloud amount.

However, reliable estimates (probable accuracy $\sim$ 10%) can be made, by using the curves indicated, provided that decadal means of daily totals are considered throughout.

12. Conclusion and suggestions for further work

By removing all known systematic errors from the basic data, and using only means of large numbers of observations, it is possible to obtain results from routine continuous radiation records which have an estimated accuracy within $\pm$ 5%. Conclusions drawn should be typical of the smoke-polluted atmosphere in which most of us live in this country.

At the present stage of the work, there come to mind several ways in which the accuracy of further measurements could be improved:-

(i) Improvement of the exposure of the instruments.

(ii) Use of a common orientation of the instruments.

(iii) Use of a more realistic assumption than that of an isotropically diffuse hemisphere.

(iv) Measurement of the instrument temperature during calibrations.

(v) Automatic integration of the solarimeter outputs, hour by hour.

(vi) Use of new heliostat drive mechanisms, with more suitable gear-ratios.

Regarding (i), a circular platform has now been constructed clear of the Observatory dome; when the instruments are resited, (ii) will be followed. New equipment has been ordered for (vi), and (v) has been successfully implemented as far as daily totals are concerned (M.R.P. 862).

13. Acknowledgements

I wish to express my gratitude to Dr. G.D. Robinson for his guidance throughout this investigation, and to Mr. D.B.B. Powell for help with the considerable numerical work and preparation of tables. Thanks are also due to Mr. J. MacDowall for help in Sec. 4(a) on exposure, and to Mr. R.H. Eldridge who planned the trials on which the errors of tabulation have been estimated in Sec. 6.

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TABLE I.

Corrections to previously published data

Period	Diffuse	Total
July 1946-May 47	reduce by 16%	Subtract 10% of corrected Diffuse
June 1947-Dec. 49	reduce by 6%	Subtract 9% of corrected Diffuse
Jan. 1950-Aug. 51	reduce by 16%	Subtract 10% of corrected Diffuse
Sept. 1951-Dec. 52	reduce by 18%	Subtract 10% of corrected Diffuse, increase by 1%
Jan. 1953-Mar. 53	reduce by 18%	Subtract 10% of corrected Diffuse, increase by 3%
Apr. 1953-June 53	reduce by 6%	Subtract 2% of corrected Diffuse, increase by 3%
July 1953-Dec. 53	reduce by 5%	Subtract 1% of corrected Diffuse
Jan. 1954 onwards	correct	Correct

TABLE II.

Corrected hourly means of Total Radiation ($mw.cm^{-2}$) for 10-day periods

		4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
J	0				tr	1.6	5.3	8.7	10.5	10.5	8.0	4.2	1.3				
	1				tr	2.1	6.7	10.3	12.8	11.5	8.5	5.7	1.9	tr			
	2				tr	2.8	7.0	12.0	14.9	12.8	7.6	7.3	2.9	0.1			
F	0				0.7	4.2	9.1	12.3	14.1	14.2	12.6	7.6	3.6	0.5			
	1			tr	1.6	7.1	10.8	16.3	16.6	17.1	14.8	10.7	6.4	1.4	tr		
	2			tr	3.6	10.2	17.0	21.6	23.2	23.1	20.5	16.6	10.1	2.8	0.1		
M	0			0.5	5.0	11.2	15.8	23.1	26.4	26.7	22.7	17.1	10.9	4.1	0.2		
	1		tr	1.9	8.4	14.9	22.3	26.3	28.9	29.2	24.8	19.5	13.6	7.1	1.2		
	2		tr	3.3	10.3	18.5	23.1	28.0	31.7	30.9	27.5	22.9	16.7	9.4	2.8	tr	
A	0		0.7	7.0	16.8	27.0	31.4	35.9	41.5	40.0	35.0	26.6	20.1	12.7	5.3	0.3	
	1	tr	2.4	10.5	21.0	33.3	41.8	48.4	50.9	50.1	45.4	37.4	30.4	17.9	8.0	1.6	
	2	tr	3.5	12.3	23.7	36.0	45.5	48.6	50.3	49.6	46.2	42.1	29.3	20.5	9.6	2.3	tr
M	0	0.2	3.9	10.7	18.4	24.6	32.1	41.6	42.9	40.9	39.0	37.6	30.4	23.2	13.6	4.2	0.1
	1	1.0	6.2	15.0	25.2	35.7	43.6	49.5	50.1	46.2	47.4	39.1	30.9	21.0	11.7	4.9	0.5
	2	1.6	7.1	15.1	24.3	33.8	38.9	46.7	47.8	49.9	46.9	41.9	34.4	25.7	15.7	7.6	1.5
J	0	3.0	11.5	21.6	31.5	41.6	49.1	58.2	58.8	60.9	55.3	50.8	41.5	30.0	19.6	9.4	2.4
	1	2.8	9.6	21.0	30.8	39.3	44.1	48.7	50.1	50.6	48.2	44.2	38.6	31.0	19.2	10.3	2.8
	2	2.8	9.6	18.6	29.1	38.5	46.6	51.6	52.6	51.6	51.2	49.3	37.5	28.7	17.1	9.9	2.4
J	0	2.3	8.8	17.0	27.8	36.9	41.8	47.0	49.0	47.6	45.1	39.7	33.2	23.6	15.5	8.4	2.1
	1	2.0	7.9	15.8	26.3	33.2	43.7	49.1	53.7	47.2	44.6	38.8	31.0	22.5	13.9	6.4	1.6
	2	1.3	7.2	17.3	28.0	37.9	46.0	51.6	54.5	54.4	51.3	42.4	33.8	25.0	16.6	6.6	1.0
A	0	0.3	5.0	13.5	22.0	32.7	37.9	44.6	48.2	48.8	45.9	39.1	31.6	22.3	13.7	5.1	0.2
	1	tr	3.9	13.0	24.4	35.7	43.8	47.0	50.9	50.8	46.5	39.5	33.0	21.3	12.0	3.4	tr
	2	tr	2.4	9.6	19.3	32.4	41.4	43.8	47.3	47.6	43.7	35.0	27.4	18.2	9.5	2.2	
S	0		0.9	6.2	15.8	26.6	35.1	40.7	45.4	42.4	40.5	32.5	24.9	13.2	6.0	0.3	
	1		0.1	3.6	11.9	22.0	28.7	33.6	35.7	34.6	34.0	27.0	20.3	11.6	3.5	tr	
	2		tr	2.1	9.5	17.5	23.6	31.3	34.3	33.6	28.9	25.9	17.8	8.4	1.7	tr	
O	0			1.0	5.8	13.2	20.9	28.9	32.4	33.5	30.1	22.7	14.3	5.6	0.5		
	1			0.1	3.6	10.3	16.0	22.0	25.8	25.7	21.4	15.2	10.1	3.8	tr		
	2			tr	1.6	6.3	10.7	16.4	19.5	20.3	17.1	12.9	6.7	1.7	tr		
N	0				0.9	5.5	10.5	15.3	17.9	17.8	14.8	10.1	4.4	0.6			
	1				0.2	3.8	9.1	13.1	15.3	14.9	12.1	7.7	2.8	tr			
	2				tr	2.4	5.9	10.3	12.6	12.8	9.6	5.3	1.6	tr			
D	0					1.4	5.0	8.6	10.7	10.8	8.8	5.2	1.2	tr			
	1					1.0	4.2	8.3	10.2	9.4	7.1	3.9	0.8				
	2					1.3	4.1	7.3	9.3	9.5	7.1	3.7	0.9				

TABLE III.

Corrected hourly means of Diffuse Radiation (mw.cm^{-2}) for 10-day periods

		4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 -10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
J	0				-	1.2	4.2	6.1	7.3	7.8	6.1	3.6	1.1	-			
	1				tr	1.6	4.6	6.5	7.4	7.7	6.1	4.3	1.5	tr			
	2				tr	2.2	5.0	7.8	9.0	8.7	7.2	5.1	2.3	tr			
F	0				0.4	3.0	5.8	8.0	9.4	8.9	7.7	4.8	2.6	0.3			
	1				1.1	4.1	6.8	10.2	11.7	11.0	9.3	6.8	4.2	1.1	tr		
	2			tr	2.7	6.6	10.6	13.7	14.3	15.1	13.6	11.4	6.6	2.3	tr		
M	0			0.3	3.6	6.9	9.8	13.7	14.4	14.3	12.6	10.5	7.1	3.4	0.2		
	1			1.2	5.6	10.1	13.8	15.8	17.0	16.7	14.4	11.2	8.5	4.9	1.0		
	2		tr	2.2	6.4	10.5	13.0	16.2	17.4	16.8	16.3	13.6	10.4	6.1	2.1	tr	
A	0		0.5	4.2	8.7	13.6	17.1	18.0	21.1	21.6	21.2	14.6	12.4	8.4	3.5	0.3	
	1		1.7	6.1	10.9	14.7	18.0	20.1	19.5	20.7	19.7	16.0	14.3	10.4	5.4	1.2	
	2	tr	2.3	7.2	12.4	17.0	20.2	22.0	22.6	22.5	21.0	16.6	14.3	11.1	6.0	1.8	tr
M	0	0.1	2.7	6.6	10.5	12.7	16.4	21.5	23.0	22.4	21.4	18.3	16.2	11.2	7.8	3.2	0.1
	1	0.7	4.1	8.7	13.2	17.6	20.3	23.1	24.8	23.0	21.6	19.1	15.4	11.1	7.4	3.6	0.4
	2	1.1	4.5	8.8	12.8	16.5	18.4	23.3	25.5	25.5	24.4	20.4	17.4	12.0	9.4	5.5	1.2
J	0	2.1	6.5	11.2	15.4	18.1	20.2	24.0	24.8	25.0	23.3	22.1	20.0	14.4	10.4	6.1	1.8
	1	2.2	6.1	10.7	16.8	20.0	22.9	26.1	26.9	27.4	27.1	24.0	19.8	16.8	11.5	6.7	2.2
	2	1.8	6.0	10.5	16.7	20.1	23.9	26.0	28.7	26.2	26.6	24.0	19.3	14.8	9.9	5.6	1.8
J	0	1.8	5.5	9.7	15.2	18.3	22.5	24.7	24.8	23.9	23.8	21.7	18.6	15.3	10.2	5.4	1.7
	1	1.4	5.1	9.2	14.9	19.8	24.7	27.3	28.1	28.6	26.2	23.7	17.8	13.9	9.3	4.9	1.3
	2	0.9	4.7	10.2	14.5	17.5	21.4	23.5	27.2	25.7	25.6	23.7	18.5	13.4	9.3	4.5	1.0
A	0	0.3	3.5	8.1	13.4	17.9	21.6	24.4	25.7	25.8	23.7	21.5	16.7	13.3	8.0	3.6	0.2
	1	tr	2.7	7.5	11.8	14.5	17.5	21.2	22.7	20.9	19.5	18.3	15.3	11.5	7.1	2.4	tr
	2		1.7	6.2	11.2	15.6	18.5	21.6	21.2	22.5	21.1	18.7	15.1	10.5	5.8	1.6	
S	0		0.6	3.9	8.7	13.5	17.5	19.5	22.0	20.5	20.2	21.3	14.0	8.6	4.1	0.2	
	1		0.1	3.0	7.8	12.2	15.0	17.8	20.2	20.3	19.2	15.2	12.0	7.4	2.7	tr	
	2		tr	1.7	5.7	10.7	13.5	16.2	18.5	18.5	16.0	13.2	9.7	5.1	1.2	tr	
O	0			0.6	4.1	8.8	13.3	16.0	16.3	15.7	14.7	11.6	8.4	4.0	0.4		
	1			tr	2.8	6.7	10.2	13.9	15.0	15.2	13.0	9.4	6.6	2.8	tr		
	2				1.3	4.7	7.5	10.4	11.7	12.1	10.5	6.9	4.3	1.0	tr		
N	0				0.7	3.7	6.0	8.4	10.1	10.1	8.7	6.0	3.5	0.4			
	1				0.1	2.9	6.2	8.8	9.6	9.3	7.9	5.5	2.5	tr			
	2				tr	1.7	4.3	6.1	7.3	7.4	6.2	3.8	1.3	tr			
D	0					1.1	3.9	6.0	7.1	6.8	6.2	4.1	1.0	tr			
	1					1.0	3.7	5.9	6.6	6.3	5.0	3.1	0.7				
	2					0.7	3.2	4.9	5.8	6.0	5.1	3.2	0.7				

TABLE IV.

Corrected hourly means of Direct Radiation (mw.cm^{-2}) for 10-day periods

		4 – 5	5 – 6	6 – 7	7 – 8	8 – 9	9 –10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20
J	0					2.0	5.7	6.8	7.8	7.5	6.0	3.8	1.0				
	1				tr	2.3	7.3	10.2	12.3	8.6	7.1	5.6	2.1	tr			
	2				0.1	2.9	6.8	11.0	13.7	10.7	10.2	7.8	3.7	0.1			
F	0				0.7	5.3	9.4	11.5	12.0	12.7	12.8	8.9	4.5	0.8			
	1				2.3	9.1	12.4	18.6	14.2	14.5	14.3	11.8	10.1	2.7	tr		
	2			0.1	3.4	10.6	15.4	16.5	16.3	16.5	15.4	14.6	12.3	4.1	0.0		
M	0			0.3	4.9	10.6	14.5	17.6	20.1	20.8	19.2	15.9	10.9	5.3	0.2		
	1			1.3	7.5	12.2	14.5	16.3	18.1	18.9	17.0	16.6	14.3	10.1	2.2		
	2		0.0	4.5	11.1	16.5	19.3	18.2	20.5	20.2	17.5	17.5	15.0	11.0	4.2	tr	
A	0		0.9	12.0	21.8	26.7	23.8	26.8	25.4	25.2	20.2	16.5	16.7	14.4	9.5	1.4	
	1		2.7	15.6	24.0	32.3	35.4	38.0	40.4	38.2	34.0	31.7	30.4	23.0	12.8	2.7	
	2	tr	6.3	16.6	25.1	32.6	36.9	35.9	35.9	36.0	35.4	35.9	29.0	25.3	15.6	5.3	0.1
M	0	0.7	6.7	14.5	17.4	20.5	23.9	26.6	25.2	23.9	25.2	26.6	26.0	25.2	20.5	9.4	0.6
	1	1.0	9.9	17.2	23.1	28.7	31.3	35.5	31.9	30.9	32.4	30.1	25.8	22.6	17.8	9.1	1.5
	2	2.8	9.5	15.7	23.2	27.4	27.7	29.3	25.9	28.9	28.3	28.6	26.8	23.7	17.6	12.0	2.4
J	0	6.0	18.5	27.3	29.8	34.1	37.0	40.8	39.2	41.9	40.6	39.8	34.4	31.2	25.7	17.1	5.7
	1	4.8	12.2	22.5	25.0	27.4	27.6	26.9	24.3	24.4	26.2	29.1	28.7	25.9	20.1	14.9	5.6
	2	4.1	11.8	18.7	20.7	26.4	26.0	29.3	26.9	28.0	27.7	31.6	25.7	25.0	18.5	17.1	5.6
J	0	3.8	12.2	17.8	21.1	24.7	28.7	26.2	27.5	27.1	26.4	23.0	17.8	15.4	13.9	10.1	3.7
	1	2.8	10.1	17.2	18.6	18.5	25.2	23.9	28.0	21.4	20.1	21.0	20.2	16.3	11.5	7.1	2.1
	2	2.1	11.8	20.1	25.9	28.7	32.8	33.8	31.7	34.4	33.1	25.2	24.3	24.5	21.2	14.2	2.4
A	0	0.9	6.8	14.6	16.8	19.7	20.9	24.5	24.7	26.9	29.4	22.6	21.4	19.0	17.1	9.5	0.7
	1	0.2	7.4	18.2	27.4	33.9	36.9	37.0	36.1	37.0	38.0	31.3	28.0	21.7	16.1	7.2	0.1
	2	tr	3.6	11.5	19.6	26.2	31.0	30.3	34.6	32.0	28.4	23.8	22.6	21.1	15.9	4.1	tr
S	0		1.7	10.3	18.9	25.3	29.3	31.7	31.2	29.8	26.7	24.0	22.2	13.8	7.4	0.5	
	1		0.3	7.4	14.7	19.0	22.8	23.3	20.3	19.9	21.1	20.7	20.0	14.6	6.5	tr	
	2		tr	2.6	9.4	16.7	18.0	22.3	22.5	23.3	19.9	22.8	20.7	12.0	3.3		
O	0			0.7	5.7	11.7	17.6	24.1	26.2	29.3	27.7	23.5	17.5	9.1	0.7		
	1			0.2	4.9	10.8	16.1	15.8	19.4	18.6	16.4	13.7	11.0	5.0	0.0		
	2			tr	1.6	5.9	8.6	13.0	16.1	17.3	15.3	14.2	9.9	2.1	tr		
N	0				1.2	8.0	14.5	17.3	18.3	16.4	15.6	11.8	7.7	0.9			
	1				0.2	5.9	11.3	15.2	17.4	16.0	13.8	9.6	4.1	0.1			
	2				tr	4.5	9.5	14.5	17.1	16.8	13.4	8.6	3.9	0.0			
D	0					2.8	7.0	9.3	10.6	13.1	11.7	8.5	2.1				
	1					0.8	4.3	7.5	11.6	10.3	6.8	4.5	1.0				
	2					1.2	6.3	9.5	11.5	11.1	7.4	4.2	0.9				

TABLE V.

Hourly means for 10-day periods of Extra terrestrial Radiation$_o$ (mw.cm^{-2}) on a horizontal surface. Computations based on Solar Constant of 138 mw.cm^{-2} (after Nicolet), reduced by 1% to "uncorrected Angstrom scale", and adjusted for annual variation of the solar distance

	19-20 4-5	18-19 5-6	17-18 6-7	16-17 7-8	15-16 8-9	14-15 9-10	13-14 10-11	12-13 11-12
J 0					7.4	21.4	31.8	37.4
1				1.0	9.5	24.6	35.0	40.9
2				3.6	14.2	29.3	40.1	45.9
F 0				5.8	20.6	35.8	47.5	52.6
1				9.1	27.0	42.6	53.5	59.4
2			3.0	14.9	34.3	50.0	60.8	67.0
M 0			5.6	20.8	40.1	56.0	66.9	72.8
1			9.3	28.6	47.8	63.6	74.4	80.4
2		2.4	13.9	35.4	54.5	70.2	81.2	87.2
A 0		5.7	21.7	42.9	62.0	77.4	88.2	94.1
1		9.1	28.4	49.3	68.2	83.6	94.0	99.9
2	1.7	12.7	34.2	54.6	73.1	88.0	98.8	104.4
M 0	4.6	18.5	39.4	59.5	77.5	92.2	102.9	108.4
1	6.8	23.1	43.8	63.5	81.3	95.7	106.0	111.5
2	7.3	26.8	47.1	66.6	83.8	98.2	108.2	113.6
J 0	10.3	29.6	49.6	68.8	85.9	99.9	109.6	115.0
1	11.9	30.8	50.7	69.8	86.8	100.7	110.3	115.7
2	12.3	31.2	51.0	70.0	86.8	100.7	110.4	115.7
J 0	11.1	30.0	49.9	69.2	85.4	99.9	109.6	114.9
1	8.9	27.9	48.0	67.5	84.3	98.3	108.3	113.5
2	7.5	24.9	45.1	64.7	82.0	96.1	106.3	111.5
A 0	5.4	20.9	41.5	61.4	79.2	93.5	103.6	109.4
1	2.5	15.2	36.2	56.5	74.3	89.1	99.4	105.0
2		10.2	30.7	51.2	69.6	84.6	95.1	100.8
S 0		6.9	24.0	44.9	63.6	78.8	89.2	95.1
1		5.8	16.6	37.6	56.5	71.7	82.5	88.5
2			10.6	31.5	50.5	66.0	76.9	82.7
O 0			7.0	24.3	43.3	58.8	69.7	75.4
1			3.4	17.1	36.3	51.4	62.3	68.2
2			1.4	10.0	28.9	44.5	55.2	61.3
N 0				6.3	21.5	36.9	47.8	53.5
1				3.5	15.8	30.9	41.8	47.3
2				1.4	10.9	25.9	36.5	42.2
D 0					7.9	22.3	32.8	38.4
1					6.6	20.1	30.6	36.2
2					6.5	19.7	30.0	35.7

TABLE VI.

Hourly means of Duration of Bright Sunshine (hours) for 10-day periods

		4 – 5	5 – 6	6 – 7	7 – 8	8 – 9	9 –10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20
J	0					0.03	0.16	0.18	0.20	0.19	0.19	0.11	0.02				
	1					0.07	0.23	0.24	0.28	0.22	0.19	0.18	0.04				
	2					0.05	0.18	0.30	0.35	0.28	0.29	0.20	0.06				
F	0				0.01	0.13	0.19	0.23	0.24	0.26	0.27	0.21	0.10	0.01			
	1				0.06	0.22	0.26	0.37	0.29	0.30	0.31	0.28	0.24	0.05			
	2				0.07	0.26	0.33	0.39	0.37	0.37	0.36	0.42	0.31	0.08			
M	0				0.11	0.24	0.31	0.35	0.41	0.45	0.43	0.37	0.31	0.12			
	1			0.02	0.19	0.29	0.35	0.34	0.40	0.36	0.35	0.35	0.34	0.26	0.02		
	2			0.07	0.27	0.38	0.40	0.38	0.38	0.40	0.38	0.37	0.36	0.30	0.07		
A	0		0.01	0.28	0.46	0.53	0.50	0.46	0.52	0.48	0.42	0.34	0.35	0.34	0.24	0.01	
	1		0.04	0.39	0.53	0.63	0.67	0.71	0.71	0.68	0.63	0.62	0.61	0.53	0.34	0.03	
	2		0.13	0.35	0.52	0.62	0.62	0.62	0.62	0.61	0.62	0.59	0.53	0.52	0.40	0.13	
M	0		0.13	0.30	0.32	0.35	0.39	0.43	0.43	0.40	0.42	0.47	0.47	0.51	0.48	0.29	0.00
	1	0.02	0.25	0.39	0.47	0.55	0.56	0.57	0.55	0.52	0.56	0.50	0.42	0.42	0.40	0.25	0.04
	2	0.05	0.25	0.38	0.45	0.50	0.47	0.50	0.47	0.51	0.53	0.53	0.49	0.45	0.40	0.35	0.08
J	0	0.09	0.48	0.57	0.54	0.60	0.63	0.67	0.63	0.67	0.65	0.63	0.63	0.59	0.54	0.51	0.17
	1	0.09	0.32	0.50	0.50	0.49	0.47	0.49	0.42	0.39	0.44	0.55	0.56	0.56	0.49	0.42	0.20
	2	0.06	0.32	0.44	0.46	0.46	0.48	0.50	0.47	0.40	0.45	0.56	0.49	0.50	0.45	0.44	0.17
J	0	0.12	0.29	0.38	0.44	0.52	0.50	0.50	0.49	0.45	0.46	0.47	0.42	0.39	0.38	0.33	0.10
	1	0.03	0.26	0.39	0.42	0.41	0.49	0.51	0.53	0.45	0.46	0.46	0.42	0.37	0.37	0.25	0.06
	2	0.04	0.32	0.49	0.55	0.56	0.59	0.63	0.60	0.60	0.65	0.56	0.51	0.50	0.53	0.39	0.07
A	0	0.01	0.16	0.34	0.35	0.43	0.43	0.50	0.47	0.52	0.52	0.46	0.47	0.42	0.43	0.33	0.01
	1		0.19	0.45	0.58	0.62	0.67	0.66	0.61	0.65	0.62	0.59	0.58	0.52	0.45	0.20	0.00
	2		0.08	0.28	0.49	0.59	0.61	0.60	0.64	0.63	0.57	0.51	0.52	0.45	0.43	0.13	
S	0		0.01	0.26	0.41	0.50	0.59	0.59	0.60	0.57	0.52	0.52	0.47	0.34	0.22	0.01	
	1			0.14	0.31	0.39	0.46	0.48	0.47	0.44	0.48	0.47	0.46	0.37	0.16		
	2			0.01	0.19	0.37	0.39	0.45	0.49	0.46	0.42	0.51	0.46	0.32	0.06		
O	0			0.00	0.12	0.30	0.43	0.50	0.58	0.59	0.60	0.55	0.47	0.24	0.01		
	1				0.12	0.24	0.35	0.40	0.44	0.37	0.33	0.34	0.28	0.13			
	2				0.03	0.12	0.19	0.33	0.39	0.39	0.36	0.37	0.27	0.05			
N	0				0.01	0.22	0.31	0.35	0.38	0.40	0.35	0.30	0.21	0.00			
	1					0.14	0.28	0.33	0.35	0.34	0.31	0.24	0.06				
	2					0.10	0.20	0.30	0.36	0.33	0.32	0.22	0.05				
D	0					0.04	0.17	0.22	0.26	0.29	0.30	0.24	0.02				
	1					0.00	0.11	0.19	0.28	0.25	0.19	0.14	0.00				
	2					0.03	0.15	0.21	0.26	0.29	0.20	0.10	0.01				

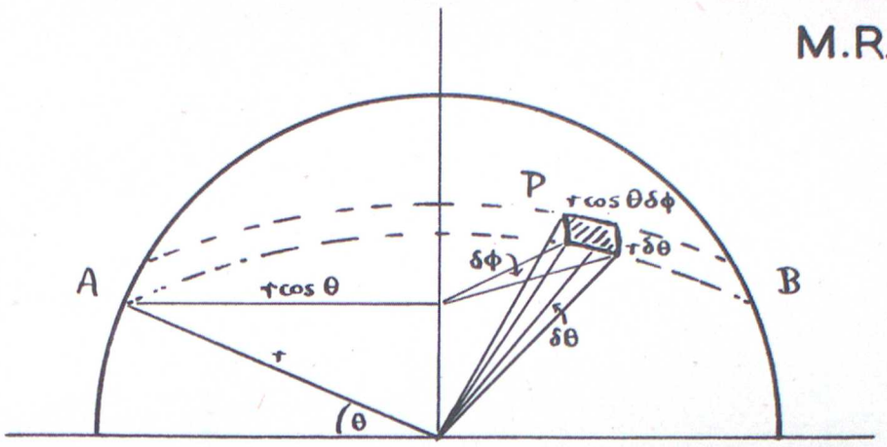

Fig. 1 - System of coordinates for obscuration calculation.

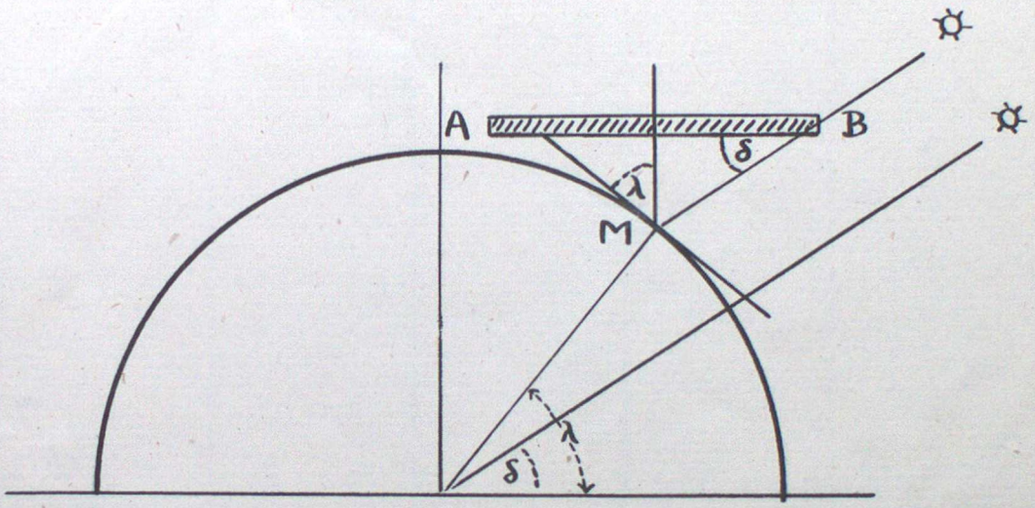

Fig. 2 - Showing the function of the shade-ring.

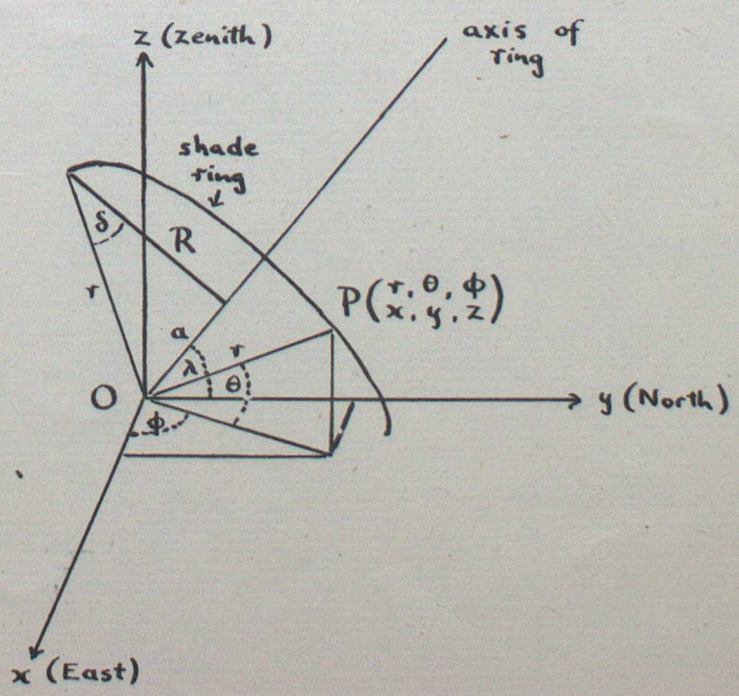

Fig. 3 - System of coordinates for projecting centre-line of ring onto θ - φ diagram.

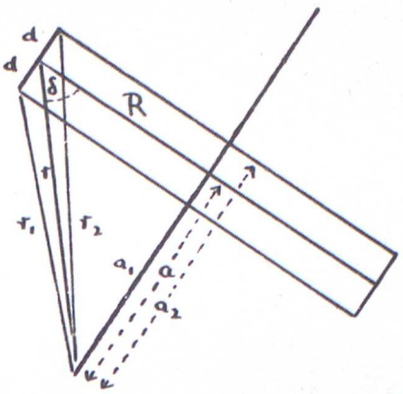

Fig. 4 - Relation between rims and centre-line of ring.

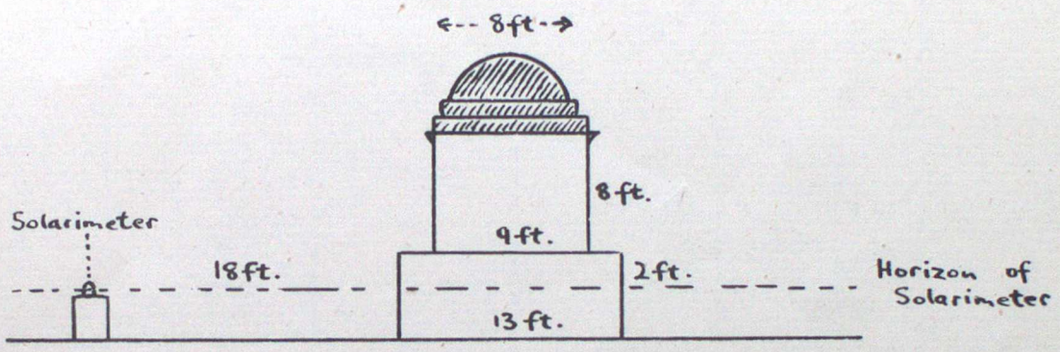

Fig. 5 - Schematic elevation of Observatory dome.

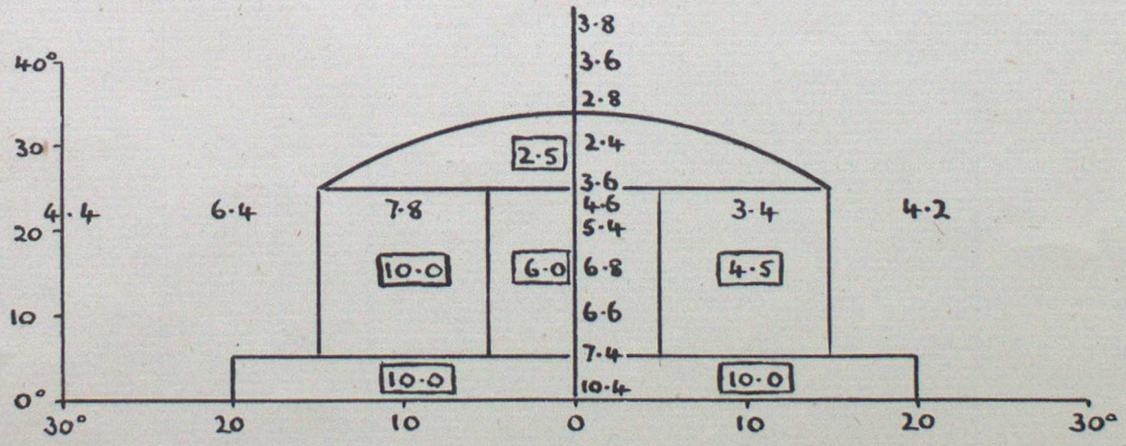

Fig. 6 - Variation of radiation intensity in vicinity of dome.

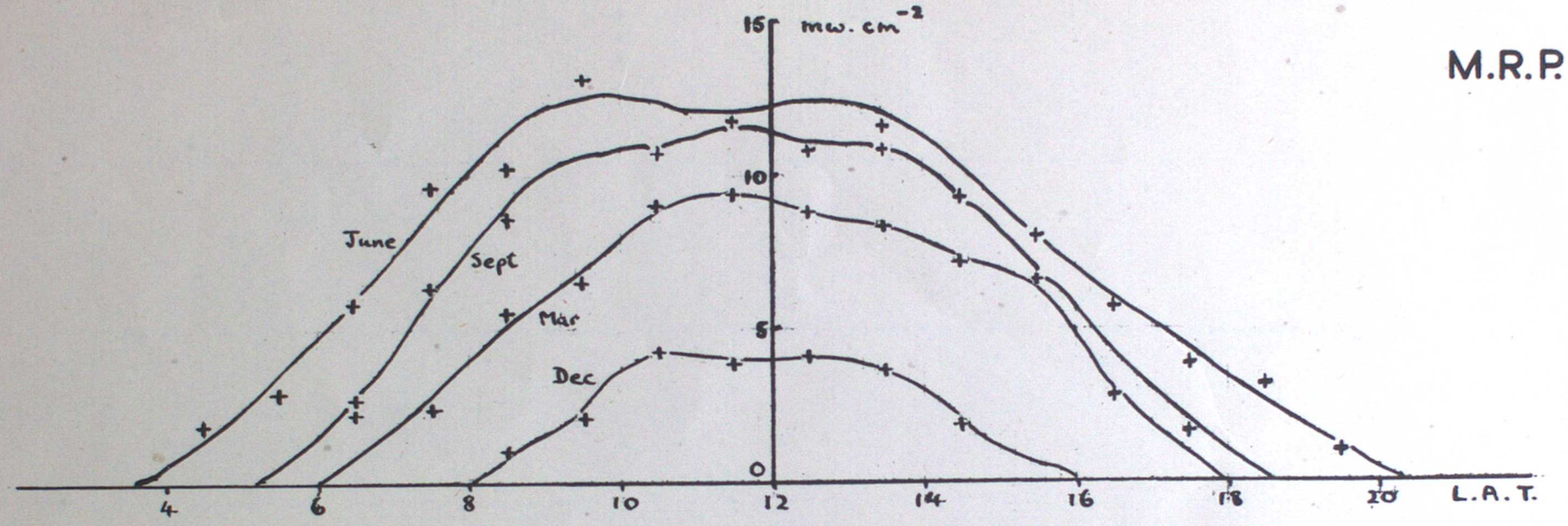

Fig. 14 - Diurnal variation of Total (= Diffuse) Radiation on overcast days.

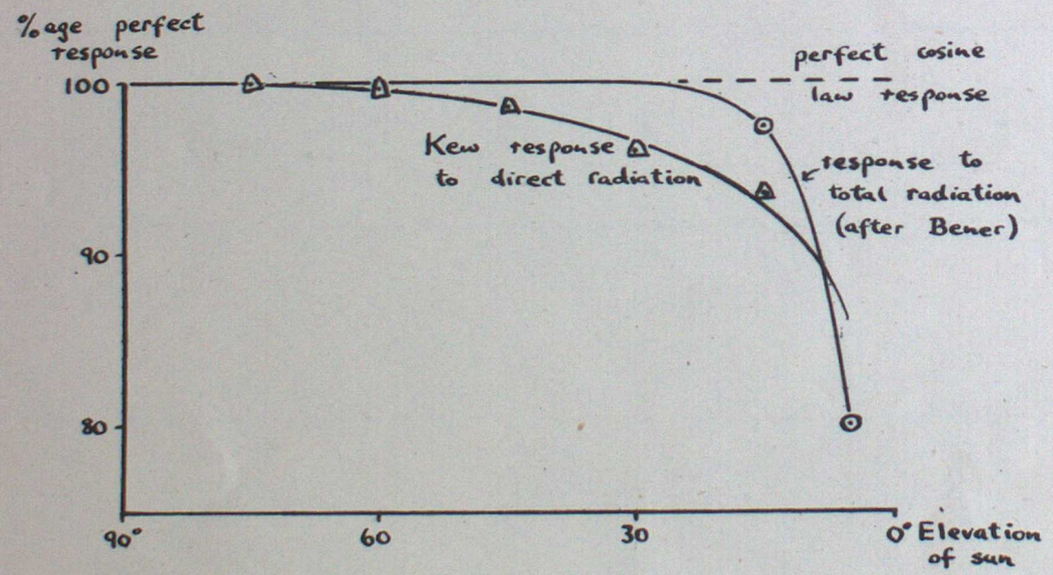

Fig. 7 - Departure of response from Cosine Law.

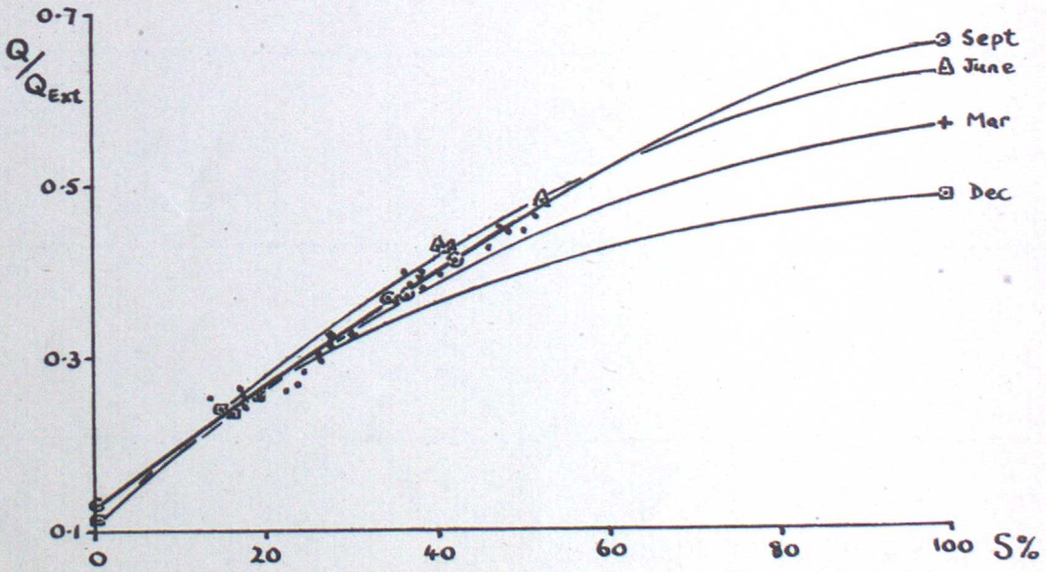

Fig. 16 - Correlation of Total Radiation and Sunshine.

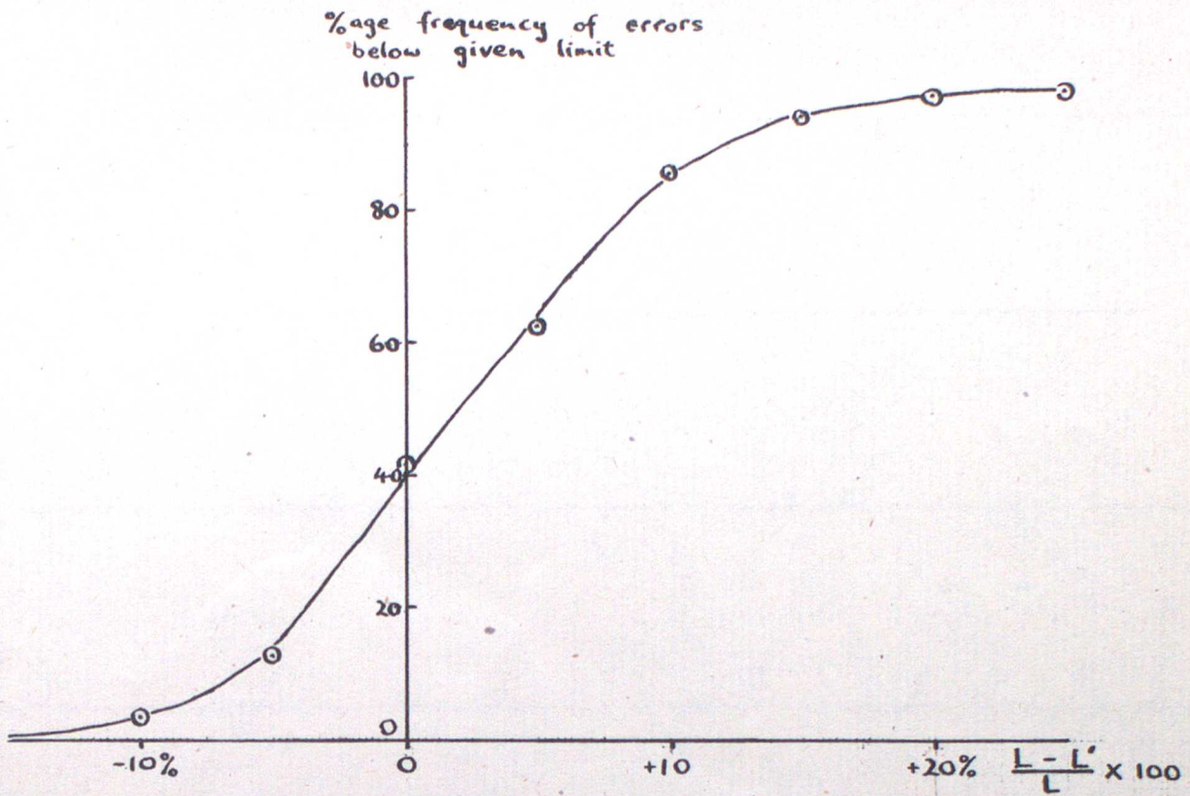

Fig. 8 - Ogive showing tabulating errors derived from independent estimations of same charts.

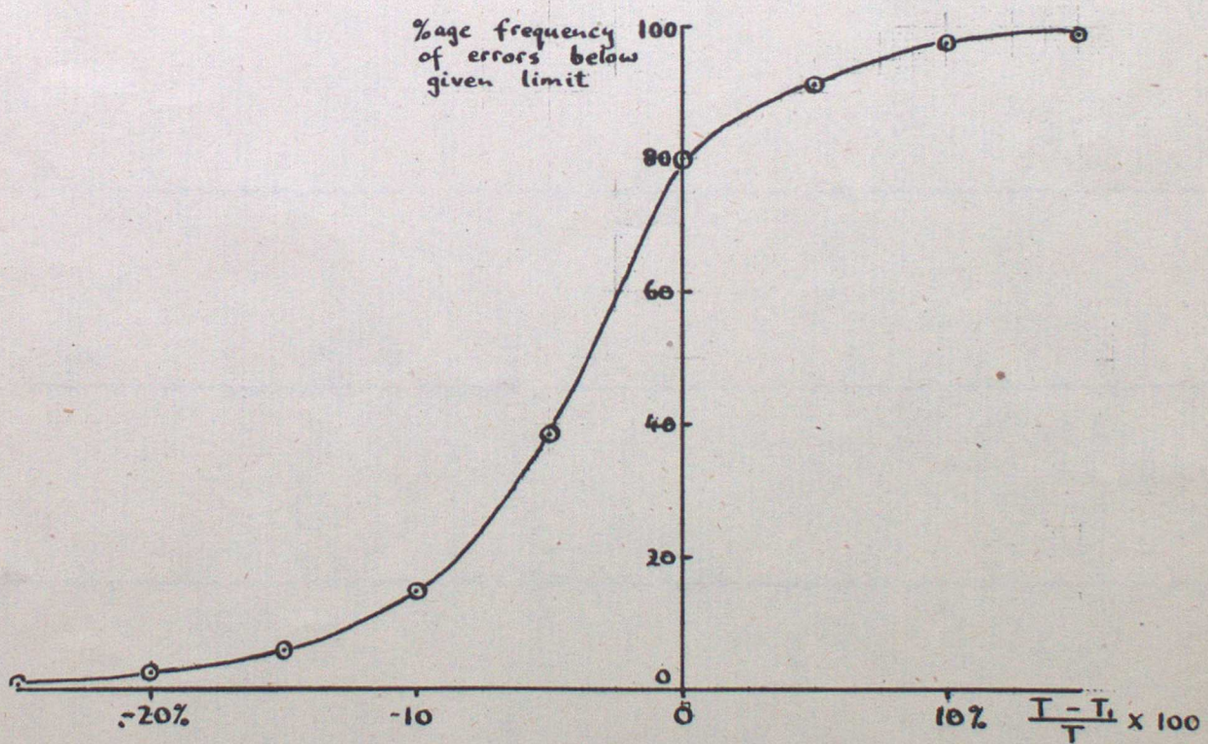

Fig. 9 - Ogive showing combined errors derived from tabulating charts of the same radiation component, but from different instruments and recorders.

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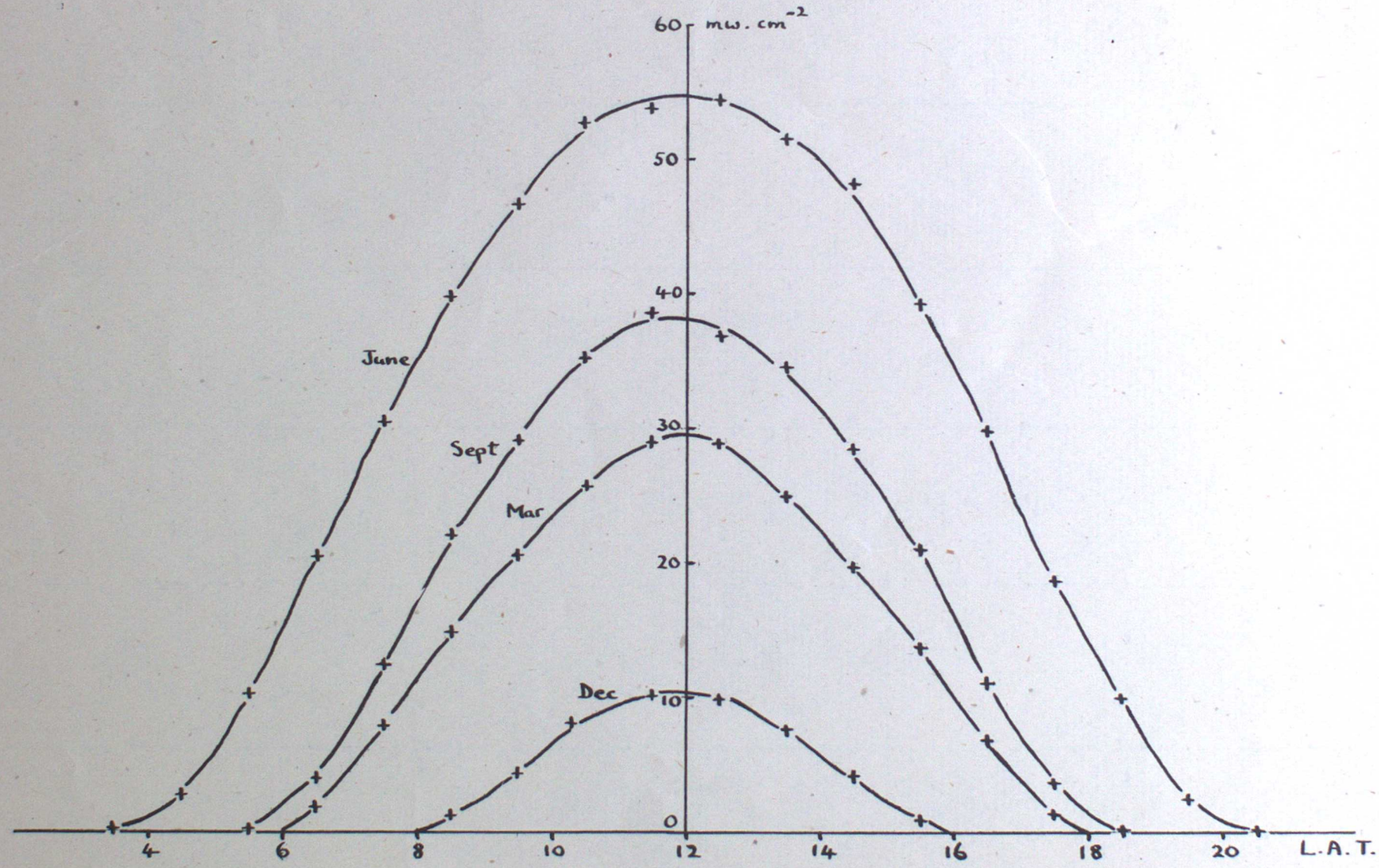

Fig. 10 - Mean diurnal curves of Total Radiation (all occasions).

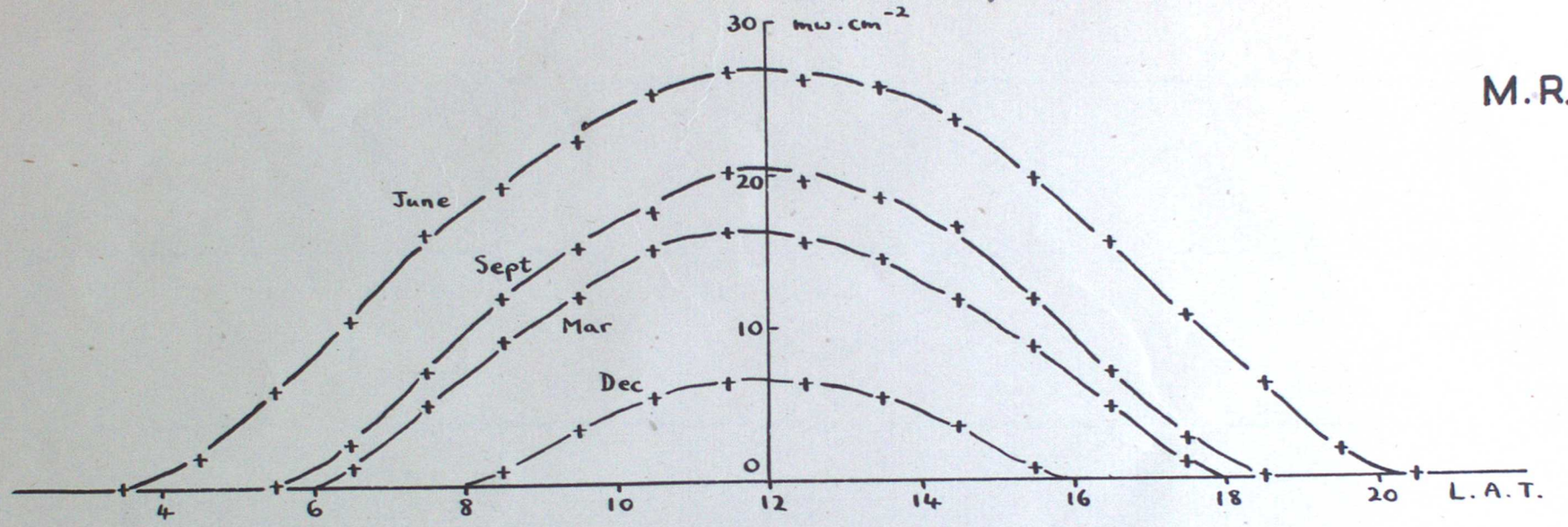

Fig. 11 - Mean diurnal curves of Diffuse Radiation (all occasions).

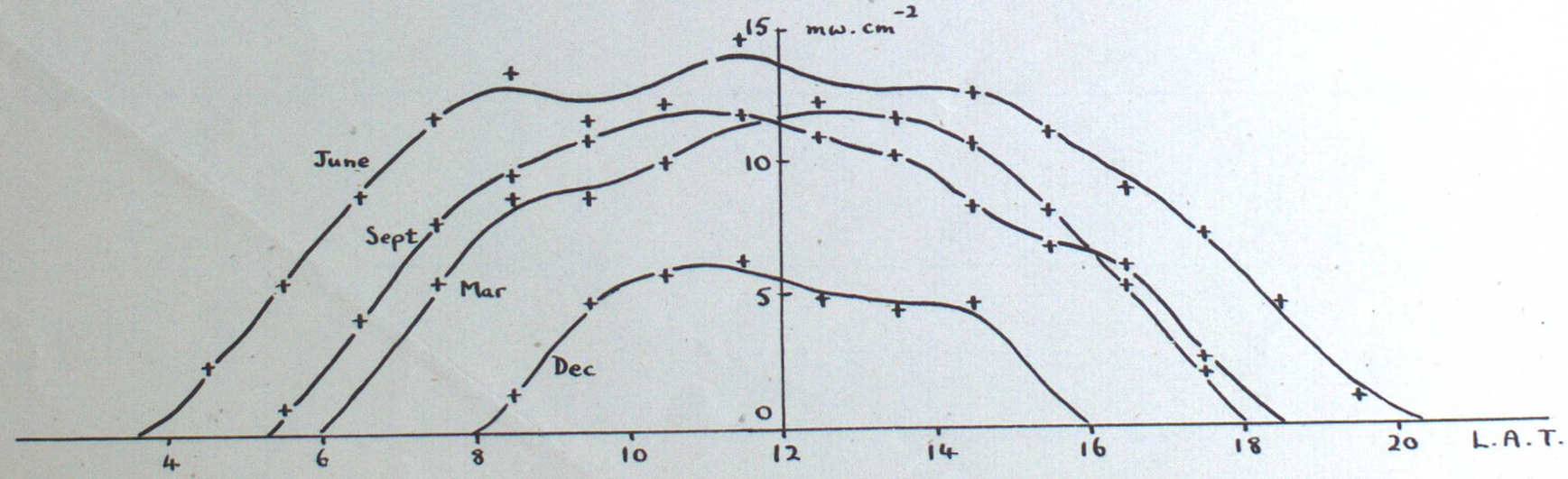

Fig. 12 - Diurnal variation of Diffuse Radiation on cloudless days.

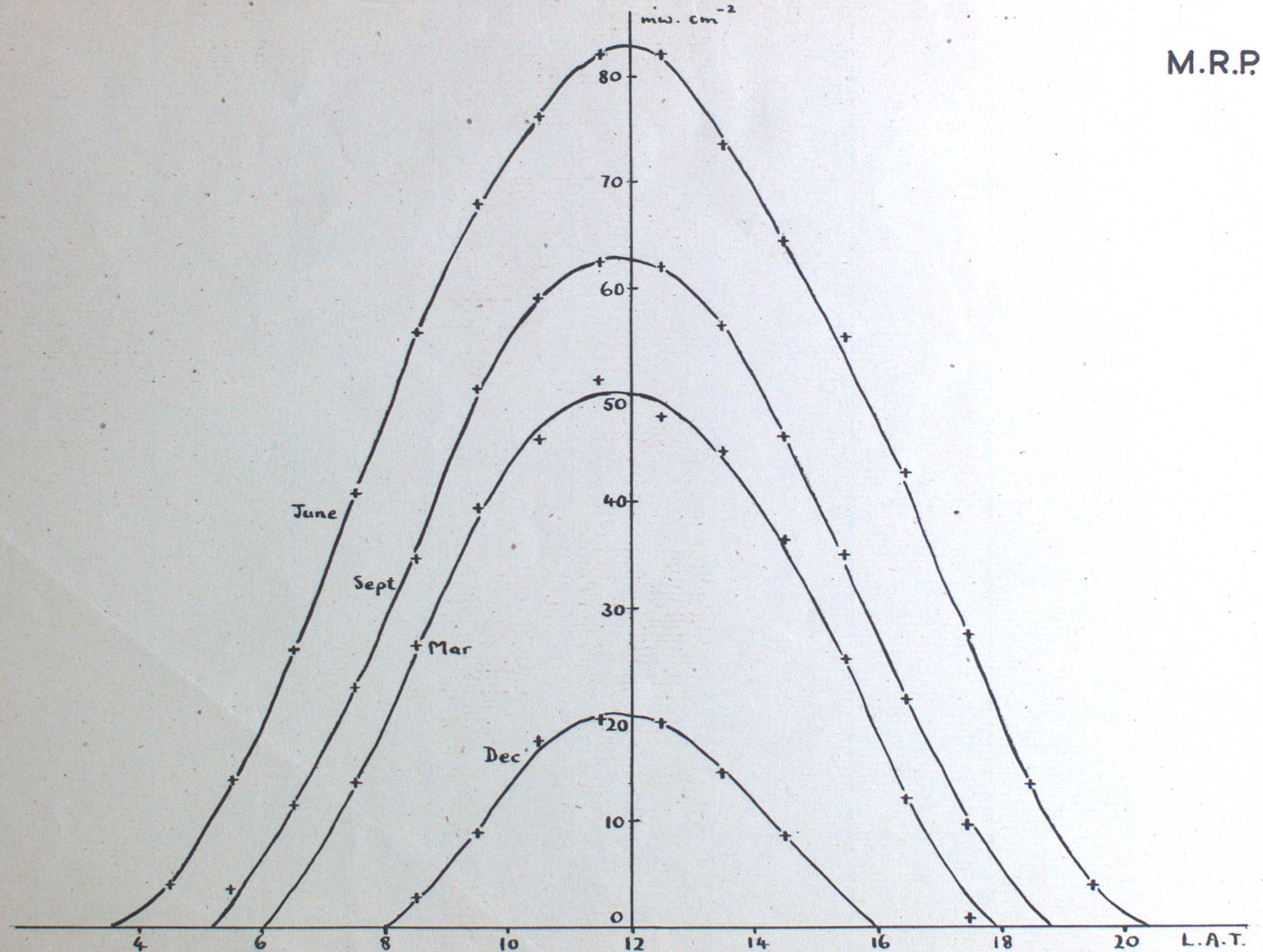

Fig. 13 - Diurnal variation of Total Radiation on cloudless days.

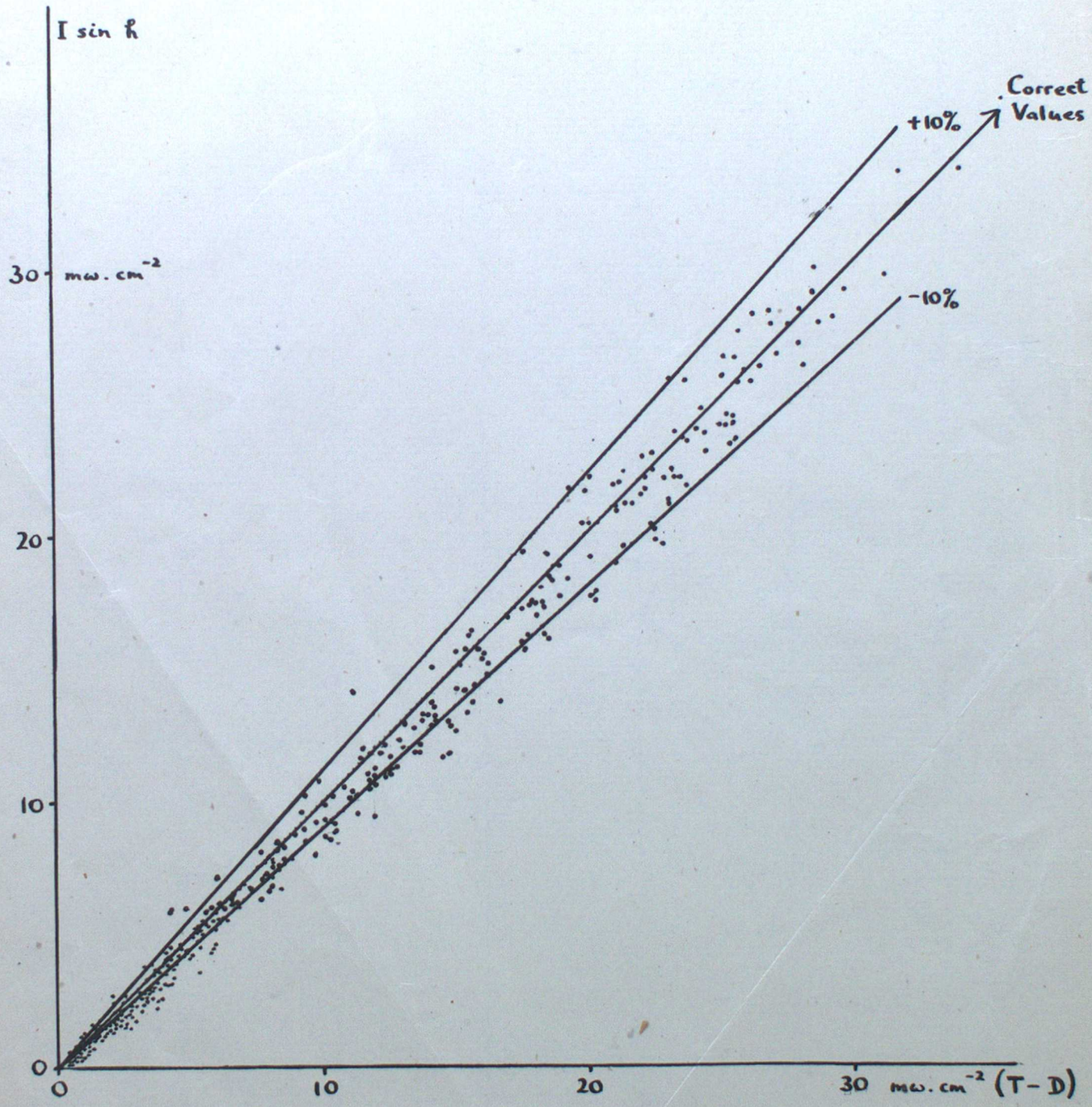

Fig. 15 - Self-consistency of the radiation measurements.